FERMILAB-Proposal-0582

Fermilab Proposal No. 582

Scientific Spokesman:

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FTS No. 388-3692

MEASUREMENT OF THE ASYMMETRY IN HIGH-$p_{\perp}$ EVENTS USING A POLARIZED PROTON BEAM AND TARGET

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January 27, 1978

39 pgs.

ABSTRACT

The investigation of spin effects at high energy is a natural and essential step for our further understanding of the behavior of hadronic constituents.

We propose to measure the asymmetry simultaneously in high-$p_\perp$ single hadron and "jet-like" events produced from the collisions of polarized protons with a polarized proton target.

I. INTRODUCTION

The investigation of the substructure of hadrons and the behavior of hadronic constituents has been one of the most active research topics in high energy physics. Large-$p_\perp$ hadron or "jet-like" event production in p-p scattering is considered to be caused by hard collisions between hadronic constituents.[1] The measurement of large-$p_\perp$ reactions near x = 0 with polarized protons will further reveal the properties of interactions between fundamental constituents by measuring the spin dependence of these hard collisions.[3,4]

In order that constituent collisions be sensitive to the initial spin state of the proton, spin must be communicated to the constituent in the hard collision. SLAC experiments[5] measuring deep inelastic scattering of longitudinally polarized electrons on longitudinally polarized protons find an asymmetry of .55 ± .10 for $0.3 \leq x_F \leq 0.5$. The result implies that parent spin is communicated to the constituent quarks. Thus, spin dependence in quark-quark collisions can be studied from the dependence on proton spins.

We propose to measure the asymmetry in large-$p_\perp$ reactions from the collisions of polarized protons with a polarized target. The polarized proton beam will be that proposed for the M-3 beam line by the mesopause workshop polarized-beam subgroup.[6] The detection of jet-like events will be accomplished with drift chambers and a transverse-momentum trigger involving photon and hadron calorimeters perfected by the Lehigh-Pennsylvania-Wisconsin group in E-395.[7a] The measurement of single-hadron production will also be simultaneously accomplished. The basic experiment is designed to extract large-$p_\perp$ events with a minimum of detector development.

We first plan to measure the spin asymmetry with only the beam polarized normal to the scattering plane:

$$A_N = \frac{E\ d^3\sigma \uparrow/dp^3 - E\ d^3\sigma \downarrow/dp^3}{E\ d^3\sigma \uparrow/dp^3 + E\ d^3\sigma \downarrow/dp^3} \quad ,$$

for the processes

$$p\uparrow p \text{ (or Z)} \rightarrow \text{single hadron} + x$$

$$p\uparrow p \text{ (or Z)} \rightarrow \text{(jet-like event)} + x \quad .$$

Here we compare constituent-interaction behavior with, for instance, QED or QCD in which asymmetries are not expected in the first order.[3] If large spin effects are observed, one may rule out that the interaction resembles simple processes like first order QED, or QCD processes.

When both the beam and target are polarized in LL or SL direction, (N: normal to scattering plane, L: longitudinal direction, S = N x L in the scattering plane), we will be able to study spin-spin dependence of the constituent scattering processes. We measure:

$$A_{LL}(s, p_\perp, x) = \frac{E\ d^3\sigma \rightleftarrows/dp^3 - E\ d^3\sigma \rightrightarrows/dp^3}{E\ d^3\sigma \rightleftarrows/dp^3 + E\ d^3\sigma \rightrightarrows/dp^3}$$

$$= \frac{E\ d^3\sigma(++)/dp^3 - E\ d^3\sigma(+-)/dp^3}{E\ d^3\sigma(++)/dp^3 + E\ d^3\sigma(+-)/dp^3} \quad .$$

The arrows indicate the beam and target relative spin directions, while + and - refer to helicity states. We expect a definite spin effect if quark behavior is consistent with QED or QCD.[3c] In the near future, we expect that theorists will come up with definite predictions of asymmetries based on the current popular models such as QCD[8] or constituent interchange models.[9] Existing models for large-$p_\perp$ events have quite different spin structure and hence can be expected to give differing predictions. Babcock, Monsay, and Sivers[10] have calculated the asymmetry using a model based on QCD perturbation theory. The asymmetries predicted have a definite positive sign. Quark pion scattering in the CIM would have a zero asymmetry.

The range of transverse momentum to be covered would be up to $p_\perp \approx 5$ GeV/c for A_{LL} at $x_F \approx 0$. In the case of single-hadron production, we can simultaneously cover up to $p_\perp = 3.3$ GeV/c or $\langle p_{\perp\,jet} \rangle \approx 4.0$ GeV/c. As a second-round experiment, we would like to observe two jets, $p^\uparrow p^\uparrow \rightarrow (\text{jets}) + x$.

II. DESCRIPTION OF THE PROPOSED EXPERIMENTS

With the apparatus proposed for this experiment, we will be able to record both single and multiparticle high-$p_\perp$ events simultaneously. The apparatus shown in Fig. 1 involves the particle detectors of E-395 slightly expanded and upgraded. Two identical calorimeters provide the $p_\perp$ trigger for both the single and multiparticle events. The three existing drift chambers will provide accurate charged-particle tracking. This apparatus will be moved to the polarized beam line. Both unpolarized and polarized targets will be used. It should be noted that the intensity capabilities of beam and detectors are ideally matched. The beam will deliver (1-3) $\cdot 10^7$ particles/pulse, while the apparatus has taken data at $1 \cdot 10^7$ particles/pulse, and may be able to take somewhat higher flux.

a. Beam (Assume 400 GeV/c primary protons)

The beam will be the polarized-proton beam proposed for the M-3 beam line. (D. Underwood et al.)[6]. The relatively large divergence of the beam (± 1 mr, $\Delta p_\perp = .3$ GeV/c at 300 GeV/c) should pose no problem in the $p_\perp$ trigger; $\Delta p_\perp$ of the trigger calorimeters, before offline corrections are applied, is 0.5 GeV/c at $p_\perp = 3$ GeV/c and increases (in value) with $p_\perp$. Beam hodoscopes with many narrow elements (~ 20) may be available from the proposed $\Delta\sigma_L$ measurements so that this effect can be unfolded offline. The beam polarization is expected to be ~50%. Intensities of 3×10^7 will be available up to momenta of 250 GeV/c and 10^7 up to 340 GeV/c. The polarization of the beam will alternate each spill providing a means of eliminating major systematic effects. Using spin precession magnets (D. Underwood et al.)[6] both transverse and longitudinal polarizations will easily be provided.

b. Target (polarized)

The target will be a polarized NH_3 target[11] for the spin-

spin asymmetry measurement. Target density will be .56 g/cm^3 and its length 10 cm. Assuming no shadowing, the polarization per nucleon will be 16%. The material in the target corresponds to that of a 0.7 meter LH_2 target. Events involving multiple interactions in the target material that fake high-$p_\perp$ products will be distinguished from true high-$p_\perp$ events using the drift chamber tracking. Extrapolating the tracks to the target will allow us to identify secondary interactions that occur 1 cm from a primary vertex (1 cm is an upper limit since 50 mrad is roughly the minimum angle). Assuming a collision length in cm for NH_3 of one seventh that in LH_2, 3.5% of the events involving high-$p_\perp$ particles (typically there are 2 or 3 per jet-like event)[7a] will have one secondary interaction of any kind in the centimeter of confusion. Information from the observed secondary interactions will allow us to correct for those that are not observed.

c. Drift Chambers

The drift chambers of E-395 will be adequate for the proposed experiment. Modification of the electronics to resolve left-right ambiguities (the chambers themselves have the capability to do this) and to allow higher rates may be desirable but not absolutely necessary.

d. Calorimeters

It is proposed to use the full right-side calorimeter of E-395. From the modules of the left-side calorimeter and newly fabricated modules, we would build an identical left-side calorimeter. This would increase the resolution of the left-side triggers, for a balanced left-right trigger, and provide a left-right symmetric apparatus for the polarization measurement.

As is detailed in the 1975 Calorimeter Conference at Fermilab[12] and the recent E-395 report,[7a] the calorimeters involve a "fly's eye" arrangement of square hadron-calorimeter modules (iron-scintillator sandwiches) and electromagnetic shower calorimeter modules (lead-scintillator sandwiches). Each arm will subtend fully 80° in both azimuth and polar angle about 90° in the center-of-mass (1.8 sr per arm). Inexpensive plastic scintillator ("plexipop") is used. The light output from these is sampled with fluorescent bars and specially designed photomultiplier tubes. The modules are distinguished by their uniform efficiency (to a few percent across their area) and by their lack of a high-energy tail which would otherwise complicate the resolution unfolding of a steeply falling spectrum.

TRIGGERS

We plan to define triggers in two ways. The first is the standard "jet" trigger. A weighted sum of calorimeter pulse heights--proportional to the total $p_{\perp}$ of the event--must exceed some threshold to trigger the apparatus. In addition, we plan to trigger on "single-particle jets"--charged or neutral single-particle events with large $p_{\perp}$. In E-395 one longitudinal calorimeter segment was selected for such a trigger. For the present experiment, we plan to install a trigger that would allow us to use the entire calorimeter. The trigger is complicated by the lateral growth of the hadronic shower. This in turn requires the inclusion of several modules lateral to the shower axis in the downstream portion of the calorimeter. In the upstream segment of the calorimeter one and only one module may fire. Such a trigger will have to be "home built".

The left-right trigger for both single and multiparticle jet-like events will be used simultaneously.

RATES

Table I indicates the accuracy to which we will be able to measure the asymmetry A_N for polarized beam only. Table II indicates the accuracy to which we will be able to measure A_{LL}. We assume the following:

$\Delta p_\perp$ = .25 GeV/c

$\Delta\Omega$ = fiducial solid angle for two 1.8 sr calorimeters is

a) 1.2 sr for multiparticle events (1/3 the solid angle of the calorimeters)

b) 2.4 sr for single-particle events (2/3 the solid angle of the calorimeters)

The y distribution of events is assumed flat.[7b, 13]

ρ_{LH_2} = .072 g/cm^3

Length (LH_2) = 100 cm

ρ_{NH3} = .56 g/cm^3

Length (NH_3) = 10 cm

Beam Polarization, $P_B = .5$

Effective Target Polarization, $P_T = .16$

10^5 Pulses (250 hours) for A_{LL}

2×10^4 Pulses (50 hours) for A_N

Incident Beam intensity: 10^7/pulse

The accuracies in asymmetry measurements are calculated as:

$\Delta A_N = 1/(P_B \cdot \sqrt{N})$ and $\Delta A_{LL} = 1/(P_B \cdot P_T \sqrt{N})$, *where N is the total* number of events.

Table I: ΔA_N, accuracy in asymmetry measurements

$<p_{\perp jet}>^*$ (Equivalent)	$p_\perp$ (single hadron)	ΔA_N (single hadron)	$p_{\perp jet}$	ΔA_N(jet-like)
		p_{lab} = 200 GeV/c		
3.6 GeV/c	3 GeV/c	1%	3 GeV/c	< 1%
4.8	4	2%	4	< 1%
6.0	5	10%	5	1.4%
			6	5%
		p_{lab} = 300 GeV/c		
3.6 GeV/c	3 GeV/c	<1%	3 GeV/c	< 1%
4.8	4	1%	4	< 1%
6.0	5	6%	5	1%
			6	3%

Table II: ΔA_{LL}, accuracy in asymmetry measurements

$\langle p_{\perp\,jet}\rangle^*$	$p_\perp\binom{\text{single}}{\text{hadron}}$	$\Delta A_{LL}\binom{\text{single}}{\text{hadron}}$	$p_{\perp\,jet}$	ΔA_{LL} (jet-like)
		$p_{lab} = 200$ GeV/c		
3.6 GeV/c	3 GeV/c	1%	3 GeV/c	< 1%
4.8	4	6%	4	1%
			5	4%
		$p_{lab} = 300$ GeV/c		
3.6 GeV/c	3 GeV/c	1%	3	< 1%
4.8	4	4%	4	< 1%
			5	2%

*$\langle p_{\perp jet}\rangle$ is the average transverse momentum of the jet of which the single hadron is a product.[1d]

COST

Additional equipment and equipment upgrade are estimated as follows: $90K

New Calorimeter Elements, 50($1.0 K)	$50K
Drift Chamber Electronics, Upgrade	$15K
Single Particle Jet, Trigger	$25K
	$90K

In addition the increase in the number of calorimeter modules by 40% should require the use of 20K additional PREP equipment in the form of ADC's and other CAMAC units.

RUNNING TIME

We request a total of 750 hours to complete the following measurements:

System Check out and Calibration:	150 hours (parasite)
Polarization at 200 GeV/c:	50 hours
Polarization at 300 GeV/c:	50 hours
Spin-spin asymmetry at 200 GeV/c:	250 hours
Spin-spin asymmetry at 300 GeV/c:	250 hours

This would provide a measurement of the asymmetry in jet-like events access to a $p_\perp$ of 5 GeV/c at the 2% level. The asymmetry for single-particle jets could be measured to the 2% level at the $p_\perp$ of 3.3 GeV/c or an equivalent jet $p_\perp$ of 4.0. These numbers refer to the 300 GeV/c measurements.

III. SUMMARY

A polarized beam at Fermilab energies would provide an excellent opportunity to investigate spin effects as a natural and essential step for our further understanding of the behavior of hadronic constituents. Specifically, we can study the spin dependence of what is presently conceived of as quark-quark scattering.

We propose to measure the asymmetry in large $p_\perp$ reactions from the collisions of polarized protons with a polarized target. The detection of jet-like events will be accomplished with drift chambers and photon and hadron calorimeters using a high-$p_\perp$ trigger.

We request a total of 750 hours to complete asymmetry measurements at 200 and 300 GeV/c. This would provide a measurement of the asymmetry in jet-like events to a $p_\perp$ of 5 GeV/c at the 2% level at 300 GeV/c. The asymmetry for single-hadron production would be measured to the 2% level at $p_\perp$ of 3.3 GeV/c or an equivalent jet $p_\perp$ of 4.0.

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3. For instance, see theoretical talks presented in Ref. 2 by:
   a) C. K. Chen, p. 38
   b) E. Fischbach, p. 65
   c) R. D. Field, p. 88

4. F. E. Close and D. Sivers, Phys. Rev. Lett. 39, 1116 (1977).

5. SLAC Experiments (E-80 and E-130); Peter Cooper's talk in Ref. 2, p. 126.

6. D. Underwood et al., A Polarized Beam for the M-3 Line, Dec., 1977.

7. a) Univ. of Wisconsin Preprint, COO-0881-4
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   Univ. of Pennsylvania Preprint (to be published)
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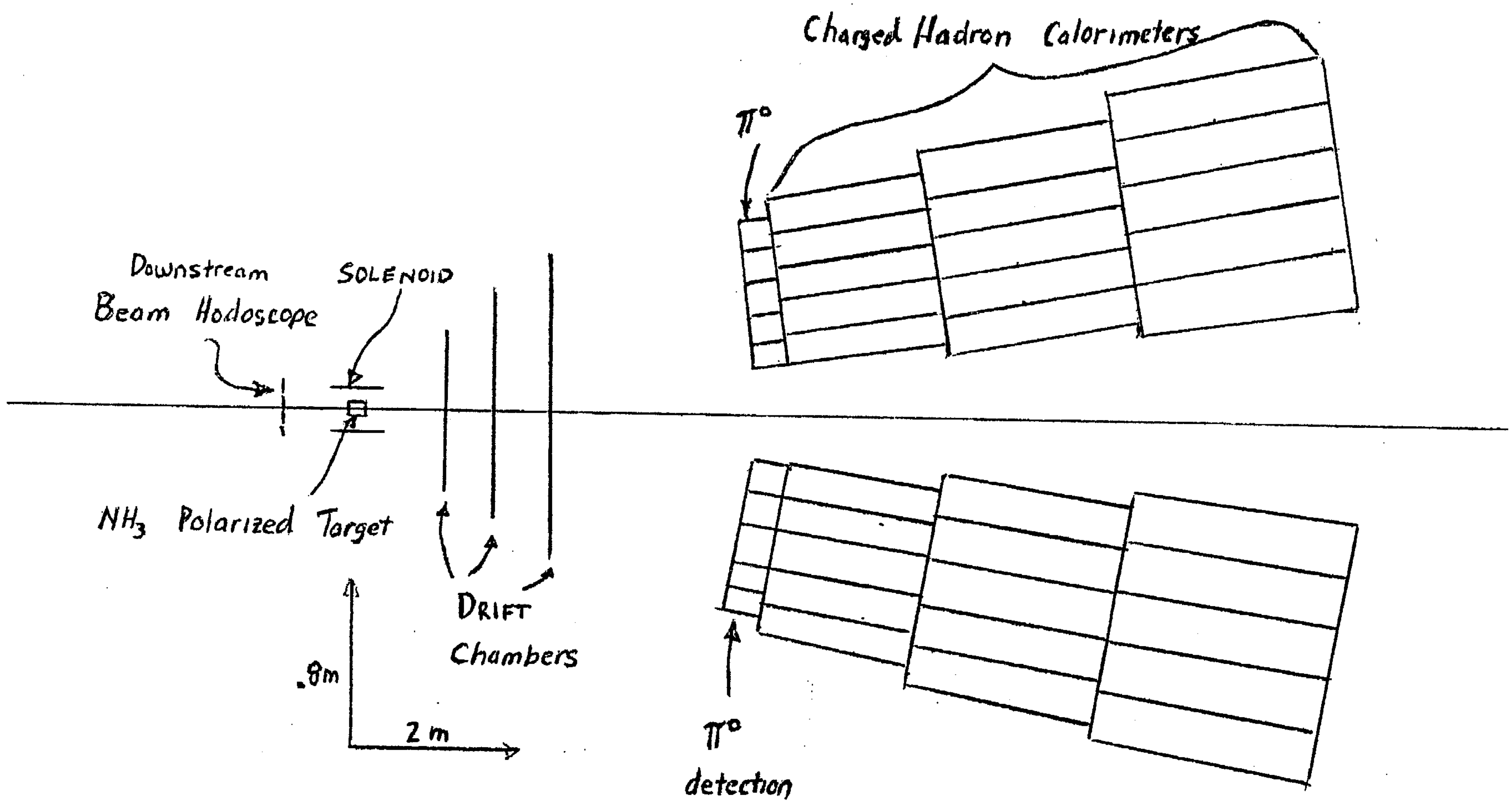

Fig. 1 Plan View of Detectors for Proposed Experiment

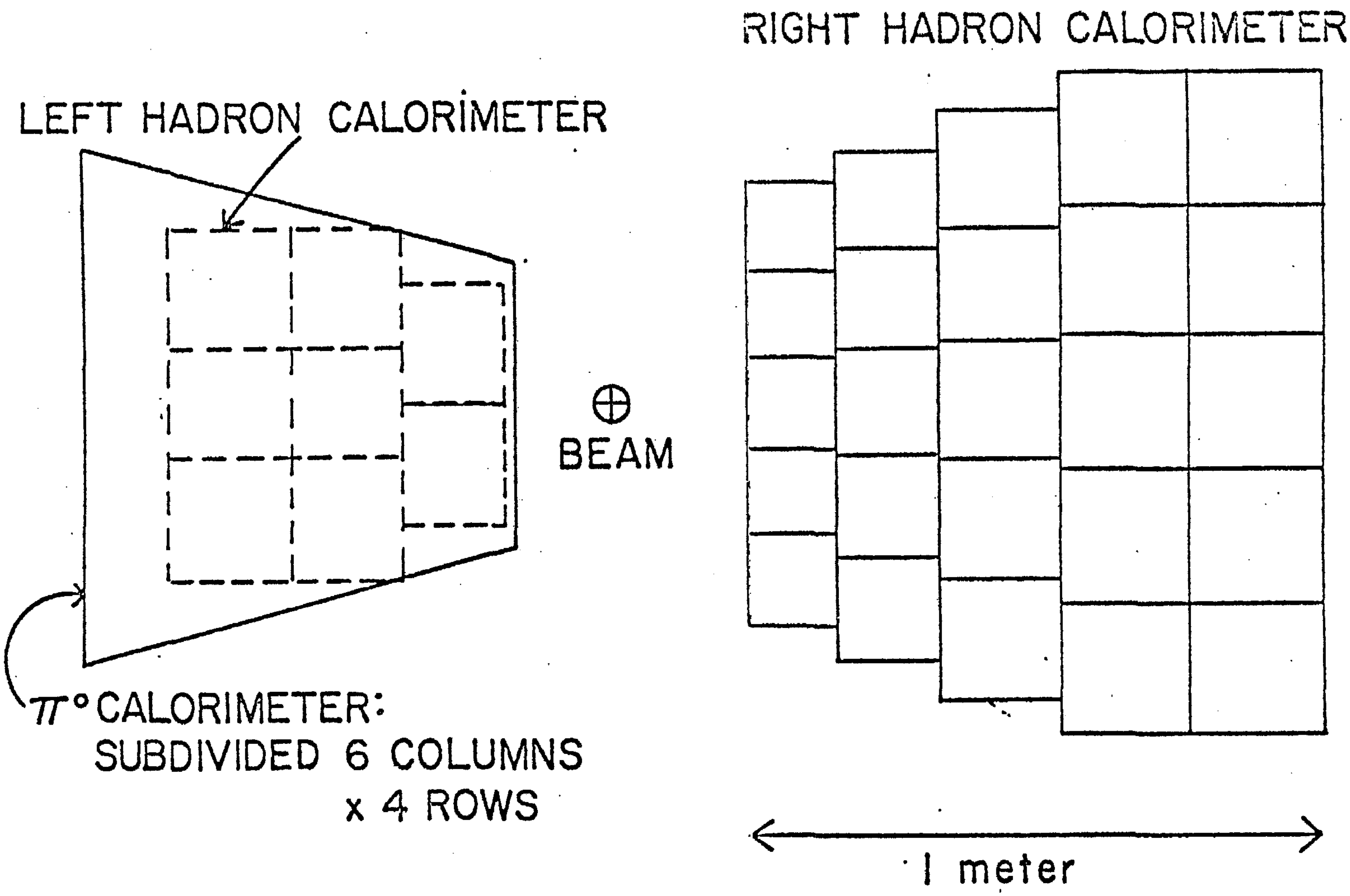

Fig. 2 Beam's Eye View of Present E-395 Calorimeters

Update

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FTS 972-6311
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2×10^4 Pulses (50 hours) for A_N

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The accuracies in asymmetry measurements are calculated as:

$\Delta A_N = 1/(P_B.\sqrt{N})$ and $\Delta A_{LL} = 1/(P_B.P_T\sqrt{N})$, where N is the total number of events.

Table I: ΔA_N, Accuracy in Asymmetry Measurements

Single Hadron Production				Jet-Like Production		
$\langle p_{\perp jet}\rangle^*$ (GeV/c)	$p_\perp$ (GeV/c)	$E(d^3\sigma/dp^3)$ (cm^2)	ΔA_N (%)	$\langle p_{\perp jet}\rangle^*$ (GeV/c)	$E(d^3\sigma/dp^3)$ (cm^2)	ΔA_N (%)
$p_{lab} = 200$ GeV/c						
3.6	3	$5.7 \cdot 10^{-32}$	1	3	$2.2 \cdot 10^{-29}$	<1
4.8	4	$1.8 \cdot 10^{-33}$	2	4	$5.8 \cdot 10^{-31}$	<1
6.0	5	$3.2 \cdot 10^{-35}$	10	5	$2.3 \cdot 10^{-32}$	1.4
				6	$1.0 \cdot 10^{-33}$	5
$p_{lab} = 300$ GeV/c						
3.6	3	$1.2 \cdot 10^{-31}$	<1	3	$4.2 \cdot 10^{-29}$	<1
4.8	4	$7.9 \cdot 10^{-33}$	1	4	$1.5 \cdot 10^{-30}$	<1
6.0	5	$2.4 \cdot 10^{-34}$	6	5	$8.7 \cdot 10^{-32}$	1
				6	$6.1 \cdot 10^{-33}$	3

Table II: ΔA_N, Accuracy in Asymmetry Measurements

Single Hadron Production				Jet-Like Production		
			p_{lab} = 200 GeV/c			
$\langle p_{\perp jet}\rangle$* (GeV/c)	$p_\perp$ (GeV/c)	$E(d^3\sigma/dp^3)$ (cm^2)	ΔA_{LL} (%)	$p_{\perp jet}$ (GeV/c)	$E(d^3\sigma/dp^3)$ (cm^2)	ΔA_{LL} (%)
3.6	3	$5.7 \cdot 10^{-32}$	1	3	$2.2 \cdot 10^{-29}$	<1
4.8	4	$1.8 \cdot 10^{-33}$	6	4	$5.8 \cdot 10^{-31}$	1
				5	$2.3 \cdot 10^{-32}$	4
			p_{lab} = 300 GeV/c			
3.6	3	$1.2 \cdot 10^{-31}$	1	3	$4.2 \cdot 10^{-29}$	<1
4.8	4	$7.9 \cdot 10^{-33}$	4	4	$1.5 \cdot 10^{-30}$	<1
				5	$8.7 \cdot 10^{-32}$	2

* $\langle p_{\perp jet}\rangle$ is the average transverse momentum of the jet of which the single hadron is a product.[1d]

COST

Additional equipment and equipment upgrade are estimated as follows: \$90K

New Calorimeter Elements, 50(\$1.0 K)	\$50K
Drift Chamber Electronics, Upgrade	\$15K
Single Particle Jet, Trigger	\$25K
	\$90K

In addition the increase in the number of calorimeter modules by 40% should require the use of 20K additional PREP equipment in the form of ADC's and other CAMAC units.

RUNNING TIME

We request a total of 750 hours to complete the following measurements:

System Check out and Calibration:	150 hours (parasite)
Polarization at 200 GeV/c:	50 hours
Polarization at 300 GeV/c:	50 hours
Spin-spin asymmetry at 200 GeV/c:	250 hours
Spin-spin asymmetry at 300 GeV/c:	250 hours

This would provide a measurement of the asymmetry in jet-like events access to a $p_\perp$ of 5 GeV/c at the 2% level. The asymmetry for single-particle jets could be measured to the 2% level at the $p_\perp$ of 3.3 GeV/c or an equivalent jet $p_\perp$ of 4.0. These numbers refer to the 300 GeV/c measurements.

III. SUMMARY

A polarized beam at Fermilab energies would provide an excellent opportunity to investigate spin effects as a natural and essential step for our further understanding of the behavior of hadronic constituents. Specifically, we can study the spin dependence of what is presently conceived of as quark-quark scattering.

We propose to measure the asymmetry in large $p_\perp$ reactions from the collisions of polarized protons with a polarized target. The detection of jet-like events will be accomplished with drift chambers and photon and hadron calorimeters using a high-$p_\perp$ trigger.

We request a total of 750 hours to complete asymmetry measurements at 200 and 300 GeV/c. This would provide a measurement of the asymmetry in jet-like events to a $p_\perp$ of 5 GeV/c at the 2% level at 300 GeV/c. The asymmetry for single-hadron production would be measured to the 2% level at $p_\perp$ of 3.3 GeV/c or an equivalent jet $p_\perp$ of 4.0.

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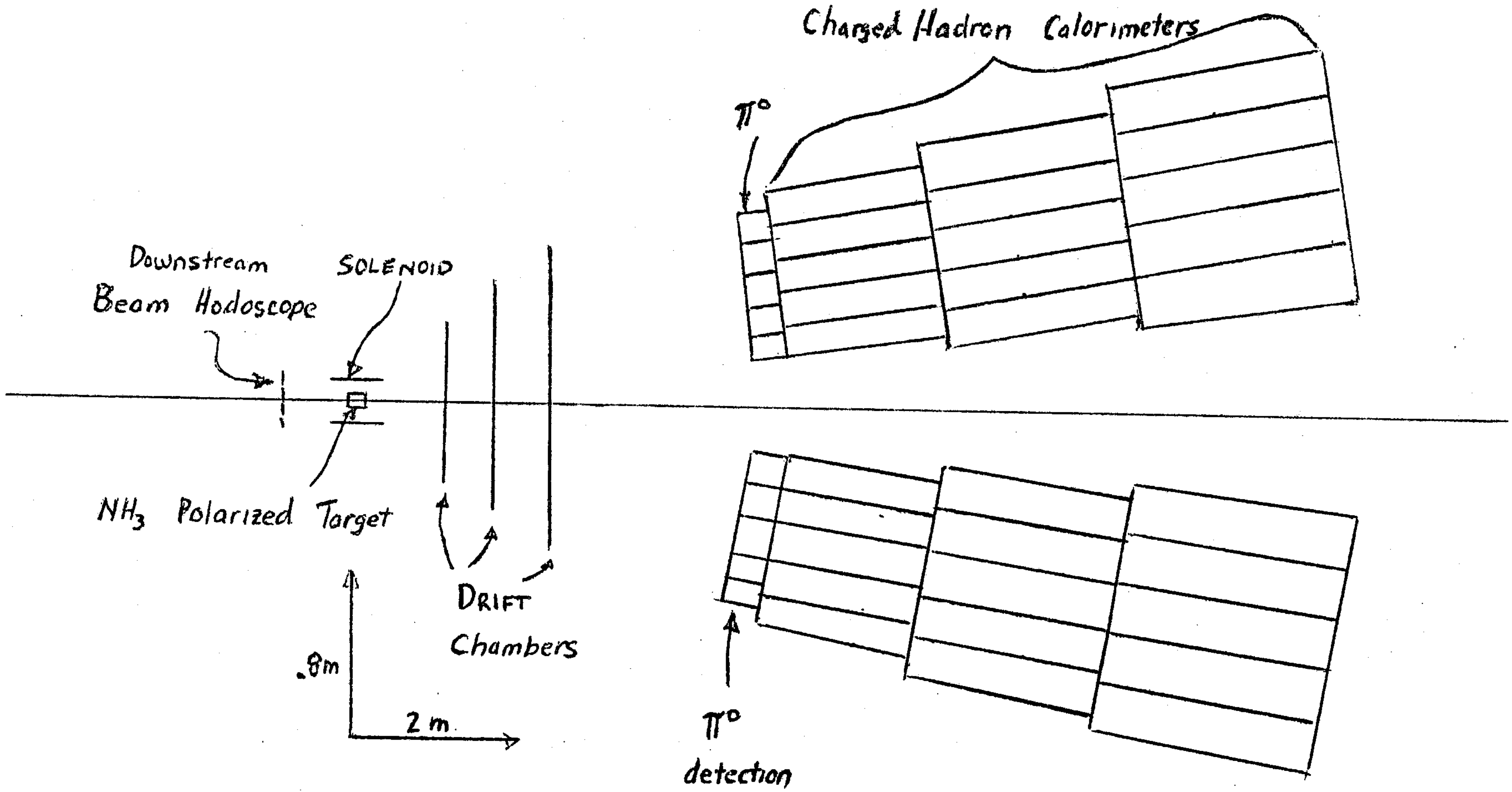

Fig. 1 Plan View of Detectors for Proposed Experiment

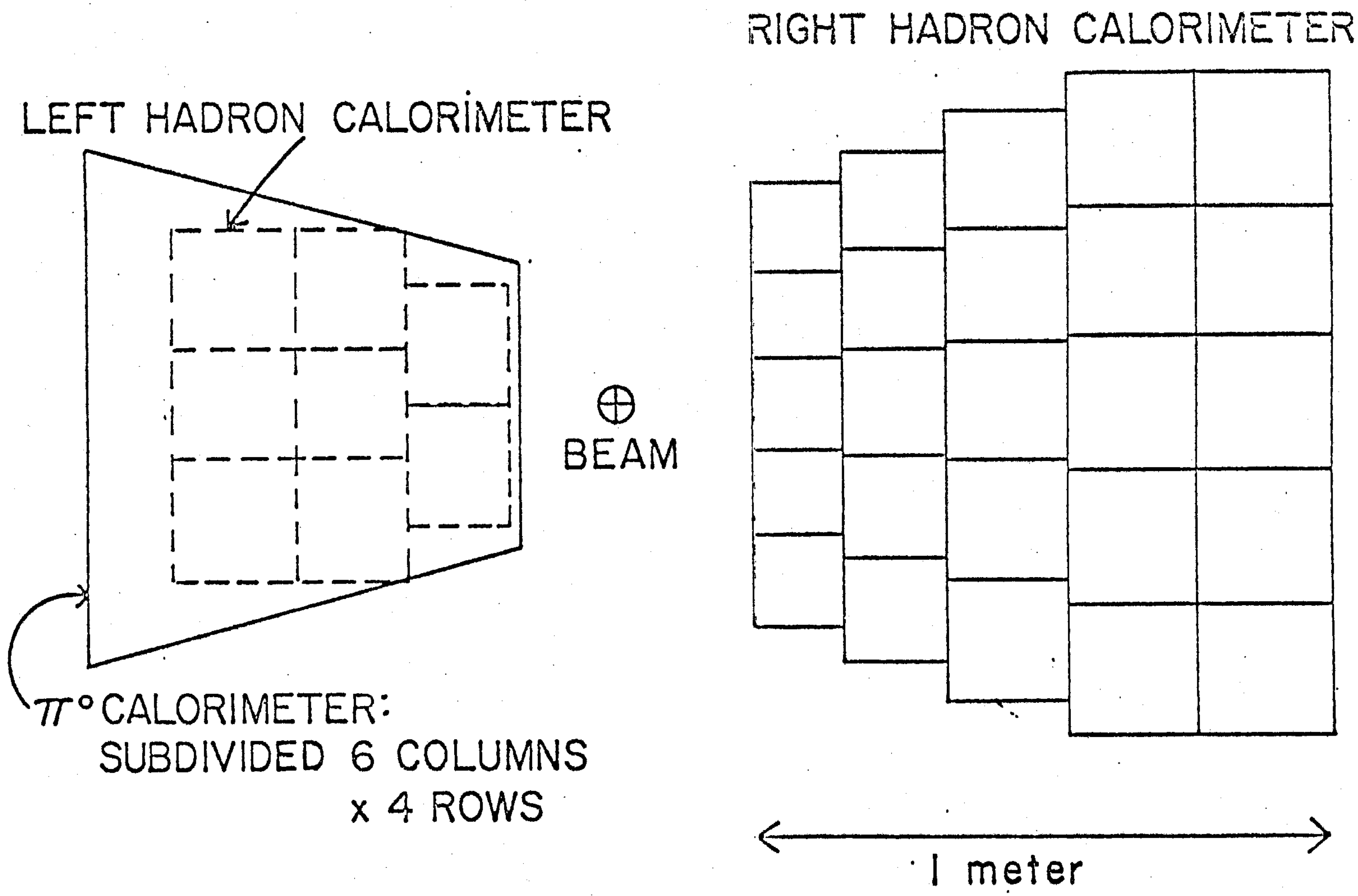

Fig. 2 Beam's Eye View of Present E-395 Calorimeters

30 May 1978

ADDENDUM TO FERMILAB PROPOSAL NO. P-582

Measurement of the Asymmetry in High-$p_\perp$ Events

Using a Polarized Proton Beam and Target

We would like to make the following additions and revisions to our proposal P-582:

1). Beam-Halo Shielding

It is quite possible that neutral particles of medium energies (5-50 GeV) present in the beam-halo can enter into the calorimeter and simulate high-$p_\perp$ events of comparable cross-section. Since there doesn't seem to exist any effective way of recognizing such a background in the data we propose to install a steel and concrete shield around the beam between the last magnet of the spin reversing system array and the target. The dimensions are 12' wide x 5' high x 10' long (steel) along the beam and 12' wide x 5' high x 20' long (concrete) along the beam.

2). Liquid H_2 Target

We need to use such a target of dimensions 5-cm diameter x 100-cm long for the A_N measurements, in which only the beam protons will be polarized.

3). Calorimeter Calibration Scheme

We propose to use the following scheme for energy calibration of the modules. The two shielding blocks will be moved, sideways from the beam line, each rolling on four wheels.

We require the last bending magnet before the target to be with a 4" aperture and 25 Kg-m in order to steer the beam into the desired element of the calorimeter. This magnet will give a 0.03 rad bend to a 20-GeV/c hadron beam which will be used for the absolute energy calibration of modules, and a 0.1-rad bend to a 5-GeV/c muon beam which will be used to balance the relative energy gain between modules. A special mechanical system will be built to rotate the magnet such that the beam will be directed to each module.

4). Rates (Page 7 to 9)

Table 1 indicates the accuracies to which we will be able to measure the asymmetries A_N for polarized beam protons only, and A_{LL} for beam and target protons, both longitudinally polarized.

We assume the following:

$\Delta p_\perp = .25$ GeV/c

$\Delta\Omega$ = fiducial solid angle for two 2.0 sr calorimeters is

a). 0.6 sr for jet-like events

b). 2.4 sr for single-particle events

$\rho_{LH_2} = .071$ g/cm^3

Length (LH_2) = 100 cm

$\rho_{NH3} = .56$ g/cm^3

Length (NH_3) = 12.5 cm

Beam Polarization, $P_B = .5$

Effective Target Polarization, $P_T = .16$

1.2×10^5 Pulses (300 hours) for A_{LL}

4×10^4 Pulses (100 hours) for A_N

Incident Beam Intensity: 10^7/pulse

The accuracies in asymmetry measurements are calculated as:

$\Delta A_N = 1/(P_B \cdot \sqrt{N})$ and $\Delta A_{LL} = 1/(P_B \cdot P_T \cdot \sqrt{N})$, where N is the total number of events.

Table 1

ΔA_N, ΔA_{LL} Accuracies in Asymmetry Measurements

	Single Hadron Production			Jet-Like Production		
$p_\perp$ (GeV/c)	$E(d^3\sigma/dp^3)$ (cm^2)	ΔA_N (%)	ΔA_{LL} (%)	N*	ΔA_N (%)	ΔA_{LL} (%)
			$p_{lab} = 200$ GeV/c			
3.0	5.7×10^{-32}	<1	<1	7.3×10^{-6}	<1	<1
4.0	1.8×10^{-33}	1	4	$.36 \times 10^{-6}$	<1	2
4.5	1.5×10^{-34}	3		$.073 \times 10^{-6}$	1	4
			$p_{lab} = 300$ GeV/c			
3.0	1.2×10^{-31}	<1	<1	17×10^{-6}	<1	<1
4.0	7.9×10^{-33}	<1	3	1.1×10^{-6}	<1	1
4.5	6.5×10^{-34}	3	9	$.32 \times 10^{-6}$	<1	2
5.0				$.056 \times 10^{-6}$	1	5

* Total measured event rate (E-395) per incident proton for a transverse momentum bite of $\Delta p_\perp = .25$ GeV/c, scaled for a liquid hydrogen target 100 cm long, accepted by the two calorimeters.

5). Cost (Page 10)

Additional equipment and equipment upgrade are estimated as follows:

New Calorimeter Elements, 70($1.5K)	$105K
Drift Chamber Electronics, Upgrade	$ 15K
Single Particle Jet, Trigger	$ 25K
	$145K

In addition the increase in the number of calorimeter modules should require the use of 30K additional PREP equipment in the form of ADC's and other CAMAC units.

6). Running Time (Page 10)

We request a total of 1000 hours to complete the following measurements:

System Check out and Calibration:	200 hours
Polarization at 200 GeV/c:	100 hours
Polarization at 300 GeV/c:	100 hours
Spin-spin asymmetry at 200 GeV/c:	300 hours
Spin-spin asymmetry at 300 GeV/c:	300 hours
Total	1000 hours

This would provide a measurement of the asymmetry in jet-like events access to a $p_\perp$ of 4.5 GeV/c at the 2% level. The asymmetry for single-particle events could be measured to the 3% level at the $p_\perp$ of 4.0 GeV/c. These numbers refer to the 300 GeV/c measurements.

7). Summary (Page 11, Last Paragraph)

We request a total of 1000 hours to complete asymmetry measurements at 200 and 300 GeV/c. This would provide a measurement of the asymmetry in jet-like events to a $p_\perp$ of 4.5 GeV/c at the 2% level at 300 GeV/c. The asymmetry for single-hadron production would be measured to the 3% level at $p_\perp$ of 4.0 GeV/c.